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**The Juvenile Salmon
Acoustic Telemetry System:
A New Tool**

**Operating Hatcheries within
an Ecosystem Context Using
the Adaptive Stocking Concept**



The Juvenile Salmon Acoustic Telemetry System: A New Tool

ABSTRACT: Limitations of biotelemetry technology available in 2001 prompted the U.S. Army Corps of Engineers Portland District to develop a new acoustic telemetry system to monitor survival of juvenile salmonids through the Columbia River to the Pacific Ocean. Eight years later, the Juvenile Salmon Acoustic Telemetry System (JSATS) consists of microacoustic transmitters (12 mm long, 0.43 g weight in air), autonomous and cabled receiving systems, and data management and processing applications. Transmitter pulse rate can be user-defined and as configured for this case study was set at 5 seconds, with an estimated tag life of 30 days and detection range of 300 m. Before JSATS development, no technology existed to study movement and survival of fish smaller than 10 g migrating long distances from freshwater and into saltwater. In a 2008 study comparing detection probabilities, travel times, and survival of 4,140 JSATS-tagged and 48,433 passive integrated transponder (PIT)-tagged yearling Chinook salmon (*Oncorhynchus tshawytscha*; mean fork length 133.9 and 135.3 mm, for JSATS and PIT-tagged fish, respectively) migrating the Snake and Columbia rivers to the Pacific, the JSATS provided survival estimates at more locations with greater precision, using less than one-tenth as many tagged fish as the traditional PIT-tag system. While designed to be optimized for juvenile salmonid survival assessment in the Columbia River basin, JSATS technology may be used in a variety of environments. Information regarding different acoustic telemetry systems from various vendors is presented and discussed relative to the nonproprietary JSATS.

El Sistema de Telemetría Acústica para Juveniles de Salmón: una nueva herramienta

RESUMEN: Las limitaciones de la tecnología biotelemétrica disponible en 2001, alentaron al Cuerpo de Ingenieros de la Armada de los Estados Unidos de Norteamérica, en el Distrito de Portland, a desarrollar un nuevo sistema de telemetría acústica para monitorear la supervivencia de juveniles de salmónidos a lo largo del Río Columbia, en el Océano Pacífico. Ocho años después nace el Sistema de Telemetría Acústica para Juveniles de Salmón (STAJs) que consiste en transmisores micro-acústicos (12 mm de largo, 0.43 g de peso en el aire) autónomos, sistemas cableados de recepción y aplicaciones para el procesamiento y manejo de datos. La tasa del pulso del transmisor puede ser definida por el usuario, pero para este estudio fue configurada a 5 segundos con un marcador cuya vida media se estima en 30 días y un rango de detección de 300 m. Antes del desarrollo del STAJs no existía la tecnología para estudiar el movimiento y supervivencia de peces de menos de 10 g que migraban grandes distancias desde los cuerpos de agua dulce hacia el mar. En 2008, un estudio comparativo sobre las probabilidades de detección, tiempo de traslado y supervivencia de 4,140 individuos juveniles de salmón Chinook (*Oncorhynchus tshawytscha*) marcados con el STAJs y 48,433 con marcas electrónicas internas (PIT-tag; la longitud media furcal de los individuos fue de 133.9 mm para los marcados con STAJs y 135.3 mm para los marcados con PIT-tag) que migraban desde los ríos Snake y Columbia hacia el mar, el STAJs brindó estimaciones de la supervivencia en un mayor número de localidades y con mayor precisión, utilizando menos de un décimo de los individuos marcados con el tradicional sistema PIT-tag. Pese a que fue diseñada para evaluar óptimamente la supervivencia de juveniles de salmónidos en la cuenca del Río Columbia, esta tecnología también pudiera ser utilizada en una variedad de ambientes. Se presenta y discute información acerca de los distintos proveedores de sistemas acústicos de teledetección en relación a la no-propiedad del STAJs.



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INTRODUCTION

Uncertainty regarding the movement, behavior, and survival of juvenile salmon (*Oncorhynchus* spp.) and steelhead (*O. mykiss*) as they migrate through large river systems with multiple hydroelectric facilities has driven much of the fisheries research in the northwestern United States over the past two decades. Population declines and subsequent listings under

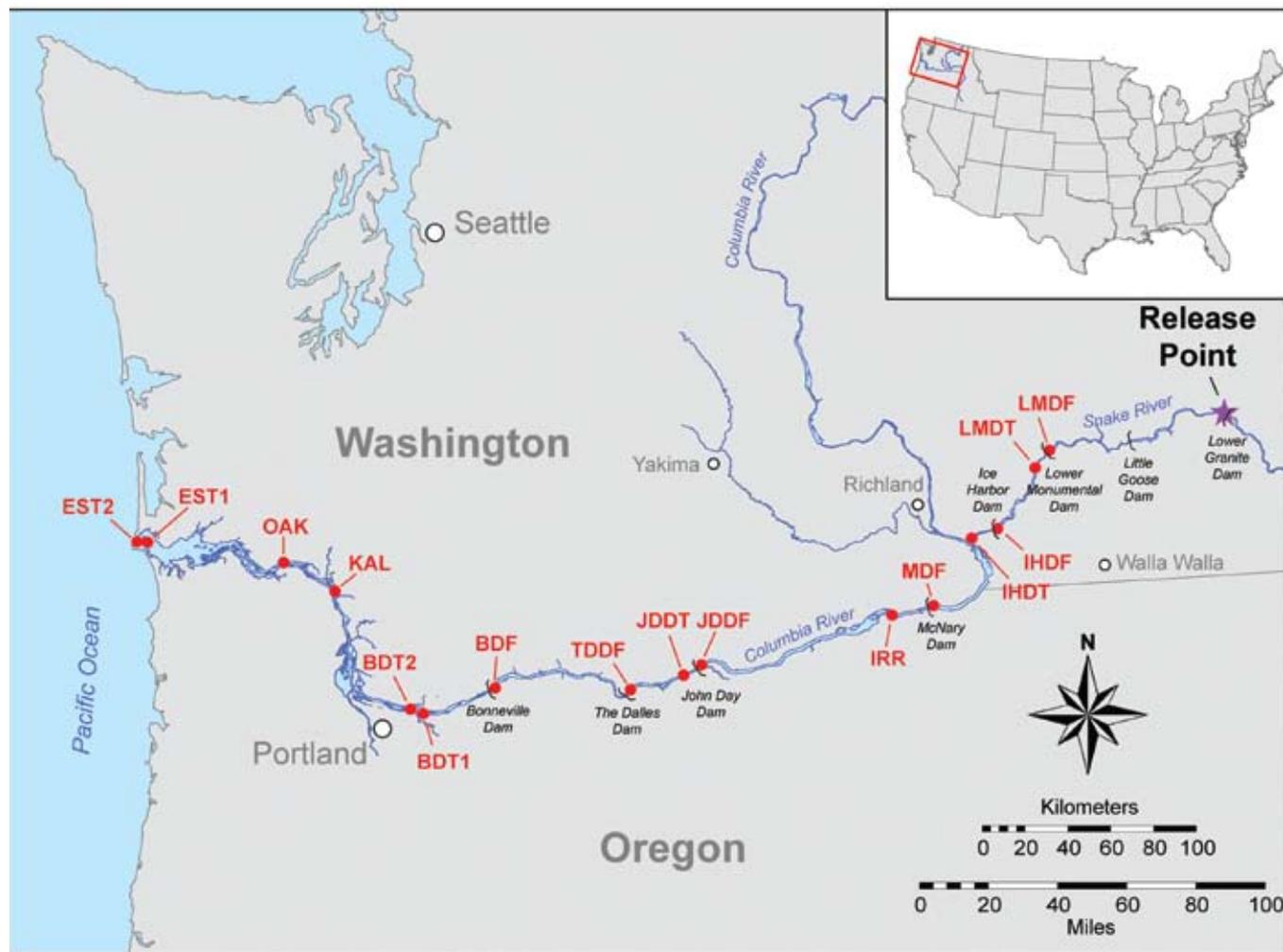
the Endangered Species Act (ESA) of several species of Pacific salmon in the Columbia and Snake river basins have increased the need to manage the effects of the hydroelectric system on these anadromous fish populations (Nehlsen et al. 1991). Based on information gaps related to juvenile salmonids, regional fisheries managers have a need to estimate behavior, timing, and survival as smolts migrate downstream through the Federal Columbia River Power System (FCRPS) and into the Pacific Ocean.

Two primary methods are currently used to monitor movement and survival of juvenile salmon and steelhead on their migration from freshwater production areas in the Columbia River basin to the Pacific Ocean. One, used over the past 20 years, is the passive integrated transponder (PIT) tag system (Skalski et al. 1998). PIT tags in current use in the Columbia River basin are 12.5 mm long and 2 mm in diameter, weigh slightly over 0.1 g in air, and are encased in glass. PIT tags are passive in the sense that the tag is energized as it passes through or near a transceiver antenna. When energized, the PIT tag transmits its unique code. To detect PIT-tagged salmonids at dams in the Snake and Columbia rivers, these antennas are located in some juvenile bypass facilities (JBF), which consist of structures and devices designed to route downstream-migrating fishes away from hydroelectric turbines and around the dam. PIT tag detection systems are also installed in adult fishways on Columbia and Snake river dams to provide

information on PIT-tagged fish migrating upstream. Because PIT tags generally have a relatively short detection range of a few centimeters to meters depending on antenna strength, the orientation of the tag when passing through the antenna, and numerous site-specific conditions (Axel et al. 2005), transceivers typically are installed within confined areas (pipes) of the JBF or narrow portions of adult fishways. Mainstem PIT-tag detection sites for downstream migrating juvenile fishes are currently limited to four dams on the Snake River (Lower Granite, Little Goose, Lower Monumental, and Ice Harbor) and three dams on the lower Columbia River (McNary, John Day, and Bonneville; Figure 1). In addition, seasonal efforts since 1995 have resulted in detections of PIT tags in the lower Columbia River, downstream of Bonneville Dam, by towing a large trawl equipped with a series of transceivers in the cod end (Ledgerwood et al. 2004).

The proportion of PIT-tagged fish detected (detection probability) on their downstream migration is relatively low; generally ranging from 5% to 70% of the fish passing a specific hydroelectric facility, varying depending on features of the JBF and dam operations (Muir et al. 2001). In recent years, emphasis on increased spill to aid migrating juvenile salmon has resulted in PIT tag detection probabilities toward the lower end of this range. The detection probability of the trawl system is lower, typically detecting about 2% of the PIT tags previously detected at

Figure 1. Study area used in JSATS microacoustic telemetry studies in the Snake and Columbia river basins in 2008. Red circles mark the autonomous receiver arrays; the star marks the release location of the implanted yearling Chinook salmon used in the case study. Cabled receivers were deployed at John Day Dam.



Bonneville Dam (Ledgerwood et al. 2004). Detection probability is important because it relates directly to the number of fish that must be tagged to produce a survival estimate with a desired level of precision. A system with a higher detection probability requires tagging fewer fish, relative to a system with lower detection probability, to produce a survival estimate with the same level of precision. Because of low detection probabilities, very large numbers of juvenile salmonids must be implanted with PIT tags and released into the Snake and Columbia rivers annually to provide enough detections to produce reasonably precise survival estimates. About two million PIT-tagged salmonids are released annually in the Snake and Columbia rivers.

The second method used to estimate survival of juvenile salmon and steelhead in the Columbia River basin is telemetry, both radio (Skalski et al. 2002) and acoustic. Radio and acoustic telemetry systems allow more flexibility in placement of detection arrays (they need not be located at a dam where fish are guided through a bypass system or fishway), have much larger detection ranges (tens to hundreds of meters), and generally have high detection probabilities, with values in the range of 80% to 100%. Therefore, studies employing radio or acoustic telemetry require fewer fish to be tagged to estimate survival and have less impact on a valuable resource already protected under the ESA.

Acoustic telemetry has several advantages over radio telemetry for studying migrating fish that are moving from large freshwater rivers to saltwater. Unlike radio signals, which are not effectively detectable in saltwater and which are attenuated significantly when passing through about 10 m of freshwater, acoustic signals are affected much less by these conditions (Winter 1996). However, radio telemetry may be better suited than acoustic systems to get precise location information on tagged fish in shallow (< 3 m) water. Acoustic transmitters do not require the trailing antennae associated with radio transmitters, which require more invasive tagging methods and may affect swimming performance, predator susceptibility, and the ultimate survival of tagged individuals (Adams et al. 1998; Brown et al. 1999; Murchie et al. 2004). However, until recently, transmitter design and battery size made acoustic transmitters too large for implantation in many of the smaller individuals within the juvenile salmonid populations of the Columbia River basin. Studies that have used active transmitters for survival studies targeted larger smolts from the overall population (Hockersmith et al. 2003; Ogden et al. 2005; Skalski et al. 2005), thereby violating a primary assumption of mark-recapture models: marked individuals are a representative sample from the population of inference.

Recent technological advancements resulting in smaller acoustic transmitters have prompted an increase in the use of acoustic telemetry to study juvenile salmonids. Since these advancements, acoustic telemetry has been used to examine the behavior and survival of yearling and subyearling Chinook salmon (*O. tshawytscha*), sockeye salmon (*O. nerka*), and steelhead migrating past dams and associated forebays of the Snake and Columbia rivers (Steig et al. 2005; Cook et al. 2007; Ploskey et al. 2007, 2008; McMichael et al. 2008). In addition, increasing emphasis on understanding the estuarine and coastal phase of the salmon life cycle has led to multiple acoustic telemetry studies to examine the behavior and survival of juvenile salmonids in estuary and near-shore ocean environments (Lacroix et al. 2005; McMichael et al. 2006; Southard et al. 2006; McComas et al. 2007, 2008; Semmens 2008).

Based on the limitations of the existing technology available in 2001, the Portland District of the U.S. Army Corps of Engineers (USACE) initiated development of a new acoustic telemetry system that would employ an active transmitter small enough for implantation in the majority of the size distribution of juvenile Chinook salmon emigrating seaward through the Columbia River estuary. Such a system would ultimately enable researchers to address many of the primary management questions related to the effects of the FCRPS on salmonid stocks listed under the ESA. For example, determining if delayed or latent mortality occurs in the lower 235 km of the Columbia River, after fish have passed through the FCRPS, is critical to understanding the effects of this hydroelectric system on listed populations.

The Juvenile Salmon Acoustic Telemetry System (JSATS) consists of microacoustic transmitters, receiving systems, and data management and processing applications. In this article, we briefly describe the current (2008) version of the JSATS and present a case study in which the detection probability, travel time, and survival probability of JSATS-tagged yearling Chinook salmon were compared to the travel time and survival of PIT-tagged cohorts as they migrated through 695 km of the Snake and Columbia rivers.

SYSTEM DESCRIPTION

Microacoustic Transmitters

The 2008 JSATS microacoustic transmitters had a weight of 0.433 g (N = 30, SE = 0.001) in air and 0.293 (0.002) g in water (Figure 2). The tags were 5.21 (0.01) mm wide, 12.00

Figure 2. JSATS 2008 microacoustic transmitter. (A; side, B; top) and pit tag (C).



(0.01) mm long, and 3.77 (0.04) mm high (thick). Mean tag volume was 0.14 (0.00) ml. Each tag transmitted a uniquely coded 31-bit binary phase-shift keyed (BPSK) signal at a frequency of 416.7 kHz and a mean source level of 155.6 (0.01) dB (relative to 1 μ Pascal at 1 m). The coded signal is transmitted over 744 μ s, resulting in an acoustic wavelength approximately 1.1 m long at 20°C. BPSK is a phase modulation technique used to convey an encoded digital signal through shifting of the signal phase (Proakis 1995). In a BPSK signal data are not carried by the signal amplitude, reducing the chance of signal corruption in noisy environments. Tags had a programmable 5-second pulse rate interval (PRI; i.e., one transmitted pulse every 5 seconds) and an expected battery life of 30 days. The PRI on tags could be changed after the tags were potted, allowing the user to select PRI rates from 2 to 10 seconds, with an estimated tag life of 20 to 70 days, respectively. Tags were activated with an acoustic signal one to two days prior to tagging.

Acoustic tag receivers (Advanced Telemetry Systems Pinger Dish II, Model SWV 3.01) were used to decode tags during tagging. A graphical user interface (GUI) developed for use with the receiver enabled the user to view and record decoded tag signals. A biologist using a laptop computer (running an application designed to store data from tagging and release events) recorded fish length, weight, tag codes, and the name of the surgeon for each fish tagged.

Fish tagged for the case study presented in this article were actively migrating smolts collected using JBF systems at Lower Granite Dam (LGR) on the Snake River. One PIT tag (Destron-Fearing Model TX1411ST, 12.5 mm \times 2 mm) and one JSATS acoustic transmitter (hereafter referred to as tags; Advanced Telemetry Systems Model SS130) were surgically implanted in the body cavity of each treatment fish. Control fish were implanted with only a PIT tag. To surgically implant the transmitters, researchers placed fish anesthetized with 80 mg MS-222/L of water on the surgery table ventral side up, inserted a silicon tube into the mouth, and supplied water continuously from two gravity-fed tanks positioned above the surgeons. One tank contained a maintenance dose of 40 mg/L MS-222, and the other contained freshwater. Surgeons ensured the proper sedation level by controlling the valves on each tank. An incision approximately 5–8 mm long was made about 3–5 mm from and parallel to the mid-ventral line anterior to the pelvic girdle. The PIT tag was inserted into the incision, followed by the acoustic transmitter, which was placed with the battery toward the anterior portion of the fish. Both tags were positioned parallel to the long axis of the fish. The incision was closed using two simple interrupted sutures (Ethicon 5–0 Monocryl, a monofilament). Surgical instruments were sanitized between surgeries and sterilized between surgery days. Fish were placed in a 120-L recovery tank with flow-through river water and supplemental oxygen following surgery and were monitored to ensure that they recovered equilibrium before being transferred to the holding and release tank. Fish were held 12 to 24 hours after surgery before they were released back into the river.

Receiving Systems

Autonomous Receivers—The primary device used to detect JSATS-tagged fish was the autonomous receiver (Sonic

Concepts Model N201). Each receiver was a positively-buoyant self-contained device that consisted of a PVC housing with a threaded coupling and O-ring to join the upper and lower portions (Figure 3). The lower housing held lithium battery packs capable of powering the receiver for 30 days. The upper housing had an externally-mounted hydrophone, water temperature sensor, pressure sensor, and internal analog and digital circuit boards. Data were stored on CompactFlash (CF) media (1 GB, SanDisk Extreme III). Each autonomous receiver was fitted with an external beacon tag that transmitted a unique code every 15 seconds, as well as a high-impact polystyrene fin to reduce drag and increase receiver stability under high flow conditions.

During the study, receivers were deployed routinely to position the hydrophone 3 to 4 m above the river or reservoir bottom in lines that typically ran perpendicular to shore. A set of receivers across the river in a specific location was referred to as an array. The standard deployment configuration consisted of the receivers affixed by a single attachment point to a short section of rope (10 mm Samson Tenex) with three small floats for additional buoyancy, and then to an acoustic release mechanism (InterOcean Systems Model 111; Figure 3). The acoustic release mechanism, which allowed the receiver to surface when triggered by an acoustic signal, was connected to an anchor by another rope that incorporated a bungee section to reduce strain on mooring system components. Receiver and anchor assemblies were deployed by a 3- or 4-person crew from

Figure 3. JSATS 2008 autonomous receiver (receiver; A). The hydrophone (B), acoustic release (C), and anchor (D) are shown along with associated mooring line sections.



a 7–11 m-long boat by lowering the assembly to the bottom of the river or reservoir. Receivers were recovered, tested, and redeployed every 28 days to replace batteries and recover data on CF cards.

Cabled Receivers—To monitor passage behavior and passage timing for JSATS-tagged fish at John Day Dam on the Columbia River, researchers deployed cabled JSATS receivers across the powerhouse and spillway. Each cabled receiver consisted of four hydrophones connected to a four-channel receiver linked to a desktop computer. Within the computer were two multichannel digital spectrum processing cards (Innovative Integration P25M), a Global Positioning System (GPS) card (Meinberg GPS 170PCI), and the software necessary to acquire and decode candidate messages from JSATS transmitters. Each computer consisted of at least three PCI slots to house the DSP (2) and GPS cards, 4 GB RAM, and a Xeon dual core 2.0 GHz (or better) processor. To monitor the primary routes of passage available to migrating fish, two hydrophones were installed at different elevations on every pier nose (one deep and one shallow) between turbine units and spillway bays, for a total of 21 systems with 84 hydrophones. Receiver clocks were synchronized to the universal GPS clock, resulting in detection time accuracy on a single system to 50 nanoseconds and across multiple systems to 150 nanoseconds.

Data Management and Processing

Data files recovered from autonomous receivers contained fish detection information as well as physical data. Each detection was recorded in a text file with an individual tag code (TagID), time stamp, receive signal strength indicator (RSSI), and a calculated measure of noise (Rx Threshold). Data files from all receivers were coded with the receiver location and stored in a database that was developed specifically for storing and processing acoustic telemetry data. To filter out detections of TagIDs that did not meet criteria (false detections), a post-processing program was developed. This program comprised a sequence of steps that included comparing each detection to a list of tags that were released (only tags that were released were kept), then comparing the detection date to the release date (only tags detected after they were released were kept). Then, a minimum of four detections in 60 seconds was required, and the time spacing between these detections had to match the PRI of the tag or be a multiple of the PRI for the detections to be kept in the valid detection file.

These criteria provided a relatively conservative approach to accepting acoustic tag detections, optimizing effective detection range. Valid tag detections were stored in a database that generated detailed detection histories for every tagged fish at all detection arrays between the release site and the mouth of the Columbia River. Detection history data were used to estimate survival of fish for successive river reaches between the release site and the Pacific Ocean. Estimates of survival were based on detection histories using the Cormack-Jolly-Seber (CJS) single release model (Cormack 1964; Jolly 1965; Seber 1965). Survival estimates were based on detections of individual fish within the Snake and Columbia rivers on two or more autonomous receiver arrays. Standard errors were calculated with the full CJS model output.

For the cabled system at John Day Dam, time of arrival at each hydrophone was recorded for all detections. Valid detections were separated from spurious detections using filtering processes similar to those described above. Time of arrival information for valid detections on four hydrophones was used to solve for the three-dimensional (3D) position of tagged fish (Watkins and Schevill 1972; Spiesberger and Fristrup 1990) out to approximately 100 m upstream of the dam. If more than four hydrophones detected the same tag signal, the four with the best configuration for 3D tracking were selected (Wahlberg et al 2001; Ehrenberg and Steig 2002). The 3D tracks were then used to determine the specific route of passage (i.e., spillway bay or turbine unit) for each tagged fish. Detections of PIT tags (in the acoustic-tagged fish) were used to determine the percentage of fish passing the powerhouse that were guided into the JBF. Using subsequent detections on downstream arrays of autonomous receivers, researchers estimated survival for fish passing through each route. Survival through each route was then used to derive an estimate of passage survival through the entire dam.

CASE STUDY: YEARLING CHINOOK SALMON MOVEMENT BEHAVIOR AND SURVIVAL

This case study involves a total of 4,140 yearling Chinook salmon implanted with a JSATS tag (5 s PRI) and a PIT tag (treatment group) and 48,433 yearling Chinook salmon implanted with a PIT tag only (control group; Table 1). Yearling Chinook salmon smolts tagged in this study had spent one winter in freshwater prior to being collected and tagged for this study. These fish were offspring of adult Chinook salmon that spawned (or were spawned, in the case of hatchery-origin fish) during the fall of 2006. All fish were captured at the JBF of Lower Granite Dam (LGR; 173 km from the mouth of the Snake River, 695 km from the Pacific Ocean), tagged, and released (about 18 h later) in the tailrace of LGR on 10 different dates between 23 April and 17 May 2008. Treatment fish were detected by 14 arrays of autonomous receivers, cabled receivers at John Day Dam, and by PIT tag detectors at dams and on the trawl as they migrated 695 km of river between LGR and the Pacific Ocean (Figure 1). Fish implanted solely with PIT tags (control group) were detected by only the PIT tag detectors.

The detection probability of JSATS tags was high at the four arrays located in the Snake River (mean = 0.908; range = 0.812–0.984) and at the six arrays located in the Columbia River between the mouth of the Snake River and Bonneville Dam (mean = 0.932; range = 0.741–0.977; Table 2). The probability of detecting JSATS tags was lower on arrays in the Columbia River downstream of Bonneville Dam (mean = 0.599; range = 0.309–0.851). The detection probability of PIT tags was low, in comparison to the detection probabilities using the JSATS, at dams on the Snake River (mean = 0.216; range = 0.128–0.325) and in the Columbia River between the mouth of the Snake River and Bonneville Dam (mean = 0.160; range = 0.115–0.232; Table 3). The probability of detecting PIT-tagged fish downstream of Bonneville Dam with the trawl also was very low (0.015 [SE = 0.003]; based on acoustic tag detections of double-tagged [JSATS+PIT] fish downstream of the PIT trawl reach).

Yearling Chinook salmon implanted with JSATS tags migrated at a similar rate as PIT-tagged fish (Figure 4). Both groups of tagged fish migrated from the tailrace of LGR downstream about 625 km past 7 large hydroelectric facilities and into the Columbia River estuary in an average of about 15 to 16 days (Figure 4). The Chinook salmon required about 8 days to migrate from the release point to the mouth of the Snake River downstream of Ice Harbor Dam (110 km), 5 to 6 days to move from the mouth of the Snake River to John Day Dam (200 km), and approximately 2 days to travel over the final stretch of the Columbia River, downstream of Bonneville Dam, to the Columbia River estuary (200 km).

Estimated reach survival rates were generally similar between JSATS-tagged and PIT-tagged fish within the Snake River. An estimated 87% of JSATS-tagged and 93% of PIT-tagged yearling Chinook salmon survived from the point of release to Lower Monumental Dam (Figure 5). Yearling Chinook salmon implanted with JSATS tags had similar estimated survival (91%) between

Table 1. Release date, mean (standard error; SE) minimum and maximum fork length (mm), and total number in each group of yearling Chinook salmon implanted with JSATS microacoustic transmitters and PIT tags (treatment group) and each group implanted with PIT tags only (control group) that were released downstream of Lower Granite Dam on the Snake River in 2008.

Release date	N	Mean	SE	Min	Max
JSATS tagged					
24-April	394	123.4	0.73	96	202
29-April	412	129.6	0.64	103	154
1-May	413	139.7	0.56	104	171
3-May	411	123.2	0.64	93	154
6-May	416	130.9	0.55	103	156
8-May	410	136.1	0.56	104	168
10-May	405	135.0	0.55	102	166
13-May	430	140.4	0.41	110	160
15-May	415	146.4	0.44	113	168
17-May	434	134.6	0.50	94	165
Total	4140	133.9	2.34	93	202
PIT tagged					
24-April	1360	126.7	0.39	87	160
29-April	2220	134.1	0.28	94	180
1-May	6261	132.1	0.18	91	227
3-May	6019	131.6	0.16	75	170
6-May	7908	138.4	0.13	56	191
8-May	5162	136.3	0.17	92	180
10-May	5911	140.2	0.14	93	188
13-May	4942	138.6	0.14	85	177
15-May	4885	137.1	0.14	84	303
17-May	3765	138.0	0.17	87	182
Total	48433	135.3	1.32	56	303

Table 2. Detection probability of JSATS transmitters on autonomous receiver arrays in the Snake and Columbia River for the 4,140 JSATS-tagged yearling Chinook salmon released in the Lower Granite Dam tailrace between 23 April and 17 May 2008. LMDF = Lower Monumental Dam forebay, LMĐT = Lower Monumental Dam tailrace, IHDF = Ice Harbor Dam forebay, IHDT = Ice Harbor Dam tailrace, MDF = McNary Dam forebay, IRR = Irrigon, JDDF = John Day Dam forebay, JDDT = John Day Dam tailrace, TDDF = The Dalles Dam forebay, BDF = Bonneville Dam forebay, BDT1 = Bonneville Dam tailrace 1, BDT2 = Bonneville Dam tailrace 2, KAL = Kalama, EST = estuary.

Array	Geographical description	River	Km from Pacific Ocean	Detection probability (P)	SE _p
LMDF	LMD Forebay	Snake	608	0.978	0.003
LMĐT	LMD Tailrace	Snake	579	0.860	0.006
IHDF	IHD Forebay	Snake	538	0.984	0.002
IHDT	IHD Tailrace	Snake	524	0.812	0.008
MDF	MD Forebay	Columbia	472	0.954	0.004
IRR	Irrigon	Columbia	452	0.962	0.004
JDDF	JDD Forebay	Columbia	351	0.977	0.003
JDDT	JDD Tailrace	Columbia	339	0.981	0.003
TDDF	TDD Forebay	Columbia	312	0.741	0.010
BDF	BD Forebay	Columbia	237	0.975	0.004
BDT1	BD Tailrace 1	Columbia	202	0.752	0.011
BDT2	BD Tailrace 2	Columbia	193	0.309	0.011
KAL	Kalama	Columbia	113	0.483	0.013
EST1	Columbia R. Estuary	Columbia	8	0.851	0.013

Table 3. Detection probability of PIT tags at JBF of hydroelectric dams in the Snake and Columbia rivers for the 48,433 PIT-tagged yearling Chinook salmon released in the Lower Granite Dam tailrace between 23 April and 17 May 2008. LGD = Little Goose Dam, LMD = Lower Monumental Dam, IHD = Ice Harbor Dam, MD = McNary Dam, JDD = John Day Dam, JDD = John Day Dam, BD = Bonneville Dam, ET = estuary trawl, JBF = juvenile bypass facility.

Detection site	Geographical description	River	Km from Pacific Ocean	Detection probability (P)	SE _p
LGD	LGD JBF	Snake	635	0.325	0.003
LMD	LMD JBF	Snake	589	0.195	0.003
IHD	IHD JBF	Snake	538	0.128	0.003
MD	MD JBF	Columbia	470	0.232	0.005
JDD	JDD JBF	Columbia	347	0.115	0.006
BD	BD JBF	Columbia	235	0.134	0.015
ET	Estuary trawl	Columbia	72	0.015a	0.003 a

a Because no PIT tag detection, or "recapture", site exists downstream of the trawl this estimate was obtained from fish implanted with a PIT tag and a JSATS tag.

Table 4. Passage routes of acoustic tagged yearling Chinook salmon passing John Day Dam during spring 2008.

Number released at LGR	N (%) detected at JDDF	N (%) of detected fish tracked	Route assignment N (% of N tracked)			
			Spill passage through deep spill	Spill passage through TSW	Guided powerhouse (JBF) passage ¹	Unguided powerhouse (turbine) passage
4140	2317 (56%)	2293 (99%)	1324 (58%)	359 (16%)	417 (18%)	193 (8%)

¹ Determined by PIT tag detections in the JBF.

Lower Monumental and Ice Harbor dams compared to PIT-tagged fish (88%). Overall, an estimated 75% of JSATS-tagged and 82% of PIT-tagged yearling Chinook salmon released at Lower Granite Dam survived to the tailrace of Ice Harbor Dam (Figure 6). About 86% and 90% of JSATS-tagged and PIT-tagged fish, respectively, survived the migration from Ice Harbor Dam to McNary Dam (Figure 5). Violations of survival model assumptions and/or low PIT tag detection probabilities at Bonneville Dam and in the estuary trawl resulted in survival estimates with large margins of error for PIT-tagged (control) fish downstream of McNary Dam. From these estimates, about 58% of PIT-tagged (control) fish survived the migration from the tailrace of McNary Dam to the tailrace of Bonneville Dam. An estimated 70% of JSATS-tagged fish survived the migration from the forebay of McNary Dam to the tailrace of Bonneville Dam. Overall, about 48% of JSATS-tagged and 43% of PIT-tagged yearling Chinook salmon released below Lower Granite Dam in the Snake River were estimated to have survived to Bonneville Dam (PIT-tagged fish detected in JBF and JSATS-tagged fish detected in the tailrace of the dam; Figure 6). About 41% of JSATS-tagged fish were estimated to have survived from release at rkm 695 to the autonomous receiver array located just 8.3 km from the Pacific Ocean (EST1; Figure 6). Because there is no detection system for PIT-tagged fish downstream of the trawl, it is unknown what percentage of PIT-tagged fish released below Lower Granite Dam survived to enter the ocean.

The deployment of acoustic receiver arrays directly upstream and downstream of multiple hydroelectric dams (Lower Monumental, Ice Harbor, John Day, and Bonneville dams) allowed us to estimate “project” and forebay survival for JSATS-tagged yearling Chinook salmon at these sites (Figure 7). Project survival in this case is defined as survival from a line approximately 500 m upstream of a dam to a point approximately 10 to 18 km downstream of that dam. Project survival estimates were relatively high at Lower Monumental (estimate = 0.961, SE = 0.004), Ice Harbor (0.952, 0.005), John Day (0.936, 0.005), and Bonneville (0.945, 0.007) dams. Reservoir survival probabilities were estimated to be 0.942 (SE = 0.004) from the tailrace of Lower Monumental Dam to the forebay of Ice Harbor Dam, 0.908 (0.006) from the tailrace of Ice Harbor Dam to the

Figure 4. Median travel time of JSATS-tagged (JSATS; treatment group) and PIT-tagged (PIT; control group) yearling Chinook salmon from release at Lower Granite Dam to PIT tag detection sites at downstream dams in the Snake and Columbia rivers in 2008. Error bars denote 95% confidence intervals. LGD = Little Goose Dam, LMD = Lower Monumental Dam, IHD = Ice Harbor Dam, MD = McNary Dam, JDD = John Day Dam, BD = Bonneville Dam, ET = estuary trawl.

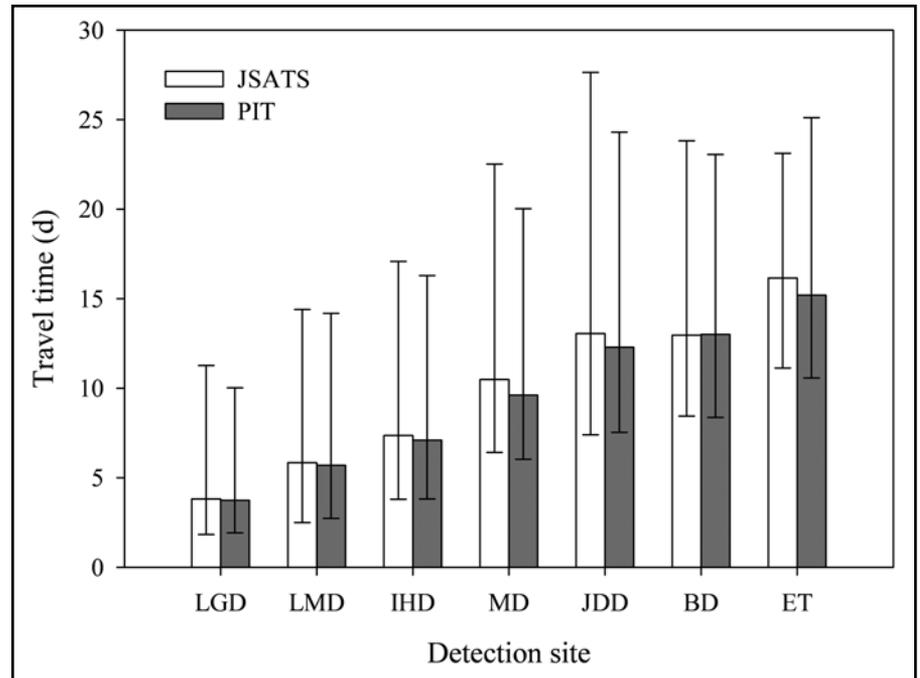
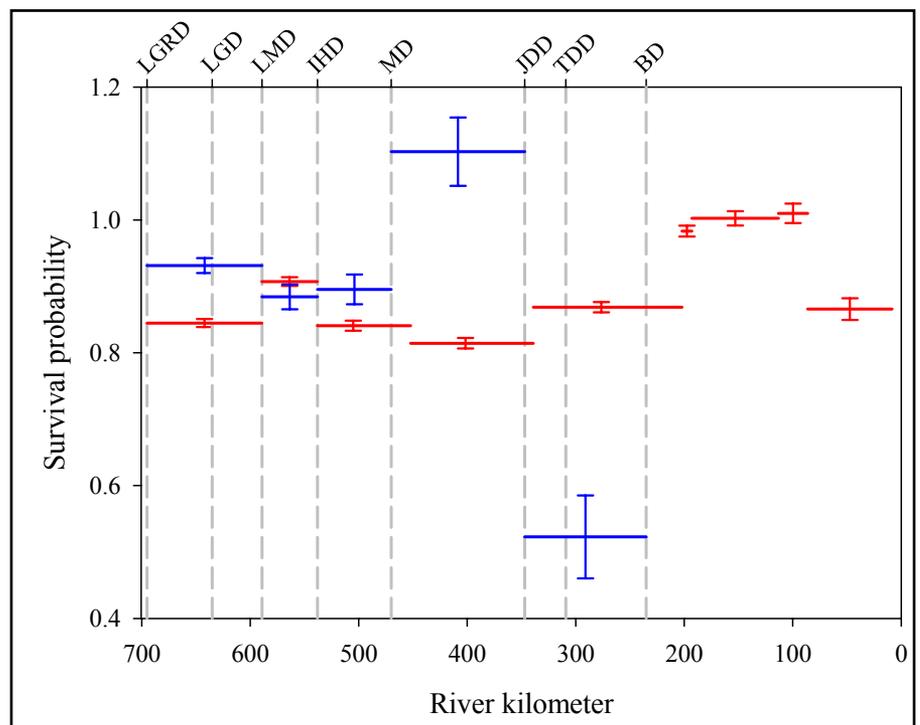


Figure 5. Reach-specific survival probability estimates for JSATS-tagged (red) and PIT-tagged (blue) yearling Chinook salmon released into the Lower Granite Dam tailrace in 2008. Error bars denote standard errors. LGR = Lower Granite Dam, LGD = Little Goose Dam, LMD = Lower Monumental Dam, IHD = Ice Harbor Dam, MD = McNary Dam, JDD = John Day Dam, TDD = The Dalles Dam, BD = Bonneville Dam.



forebay of McNary Dam, 0.884 (0.007) from an Irrigon array (located 18 km downstream of McNary Dam) to the forebay of John Day Dam, and 0.989 (0.004) from the tailrace of John Day Dam to the forebay of The Dalles Dam. Although reservoir survival estimates were generally lower than project estimates, survival rates (survival/km) were lower for fish passing through dams than through reservoirs (Figure 8).

For the 4,140 acoustic-tagged fish released below Lower Granite Dam in 2008, 2,317 fish were detected entering the forebay of John Day Dam, and 2,293 (98.9%) were assigned to passage routes using 3D tracks and PIT tag detections. Most (58%) of the acoustic-tagged yearling Chinook salmon released at LGR passed John Day Dam through deep spill routes, while 16% of the fish passed over surface flow spillway weirs (Table 4). About 26% of the acoustic-tagged fish passed John Day Dam through the powerhouse. Eighteen percent of the fish were guided into the JBF by turbine intake screens, and 8% were estimated to have passed through the turbines.

DISCUSSION

Results from the case study indicate that the JSATS is a useful tool for measuring survival over a variety of spatial scales, migratory behavior, and the effects of hydroelectric facilities on juvenile salmonids. The JSATS provided survival estimates at more locations (including survival estimates to the ocean) with greater precision, using less than one-tenth as many tagged fish as the PIT tag system in our study. The survival estimates for PIT-tagged fish downstream of McNary Dam were associated with high variability (Figures 5 and 6), possibly due to violation of survival model assumptions or low detection probabilities at Bonneville Dam and in the estuary trawl PIT tag detectors (Table 3). In general, the error associated with survival estimates calculated for fish implanted only with a PIT tag increased at each downstream detection site in 2008 (Figures 5 and 6). Conversely, the error associated with survival estimates for JSATS-tagged fish remained relatively constant over this distance because of the higher detection probabilities of acoustic tags and greater numbers of downstream “recapture” locations (i.e., acoustic arrays). The flexibility of being able to deploy

Figure 6. Overall survival probability estimates for JSATS-tagged (red) and PIT-tagged (blue) yearling Chinook salmon from release into the Lower Granite Dam tailrace to downstream PIT tag detection sites at downstream dams (for PIT-tagged fish) and to downstream autonomous receiver arrays (for JSATS-tagged fish). Error bars denote standard errors. LGD = Little Goose Dam juvenile bypass facility (JBF), LMD = Lower Monumental Dam forebay array, LMDT = Lower Monumental Dam JBF, LMDT = Lower Monumental Dam tailrace array, IHDF = Ice Harbor Dam forebay array, IHD = Ice Harbor Dam JBF, IHDT = Ice Harbor Dam tailrace array, MDF = McNary Dam forebay, MD = McNary Dam JBF, IRR = Irrigon array, JDDF = John Day Dam forebay array, JDD = John Day Dam JBF, JDDT = John Day Dam tailrace array, TDDF = The Dalles Dam forebay array, BDF = Bonneville Dam forebay array, BD = Bonneville Dam JBF, BDT1 = Bonneville Dam tailrace array 1, BDT2 = Bonneville Dam tailrace array 2, KAL = Kalama array, OAK = Oak Point array, EST1 = primary estuary array.

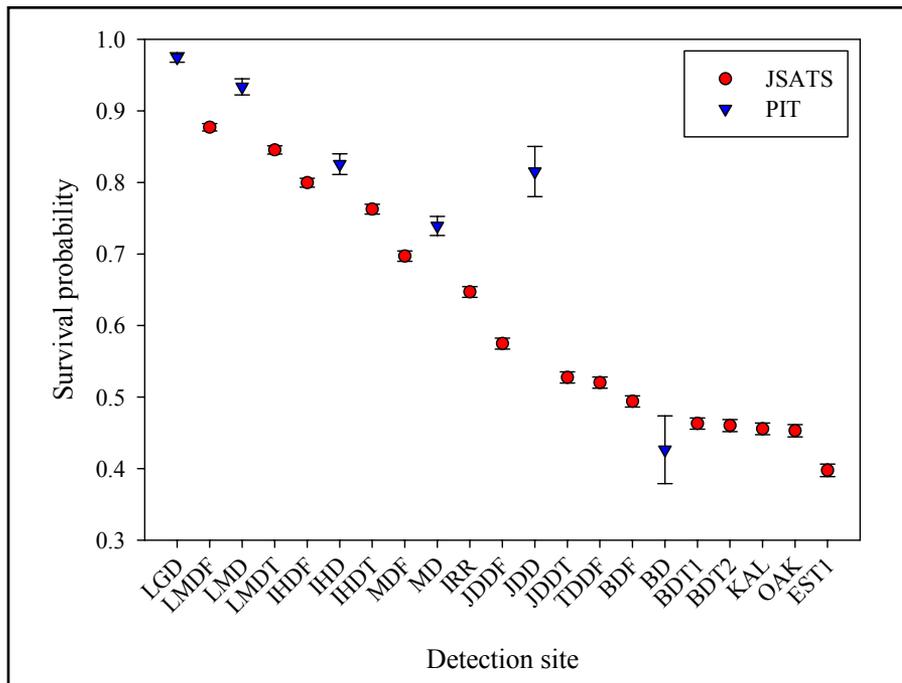


Figure 7. Forebay and project survival probability estimates for JSATS-tagged yearling Chinook salmon released into the Lower Granite Dam tailrace in 2008. Error bars denote standard errors. LGR = Lower Granite Dam, LGD = Little Goose Dam, LMD = Lower Monumental Dam, IHD = Ice Harbor Dam, MD = McNary Dam, JDD = John Day Dam, TDD = The Dalles Dam, BD = Bonneville Dam.

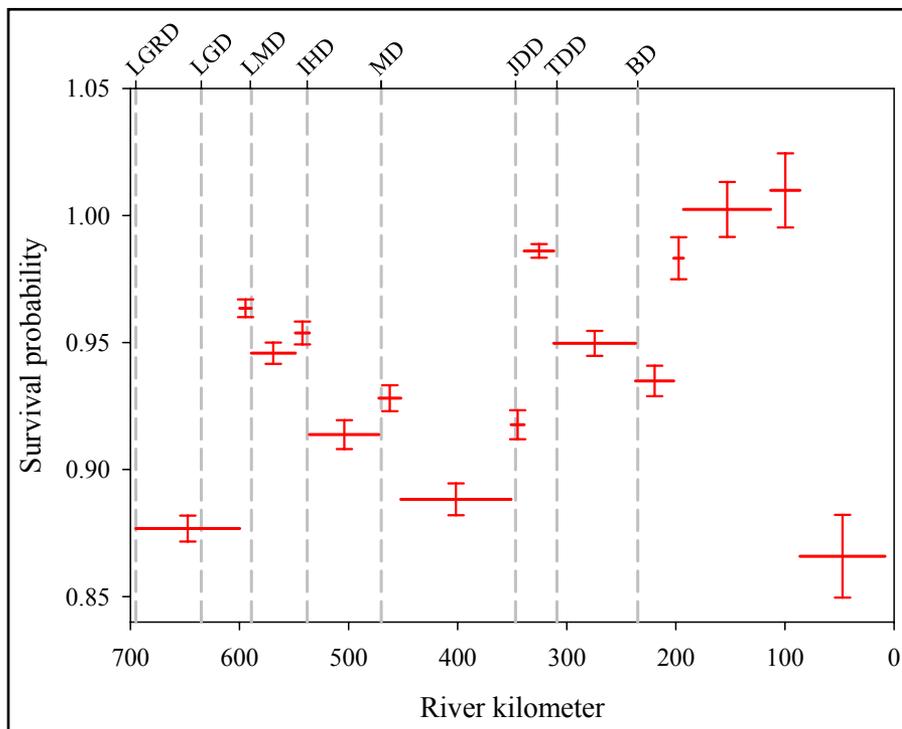
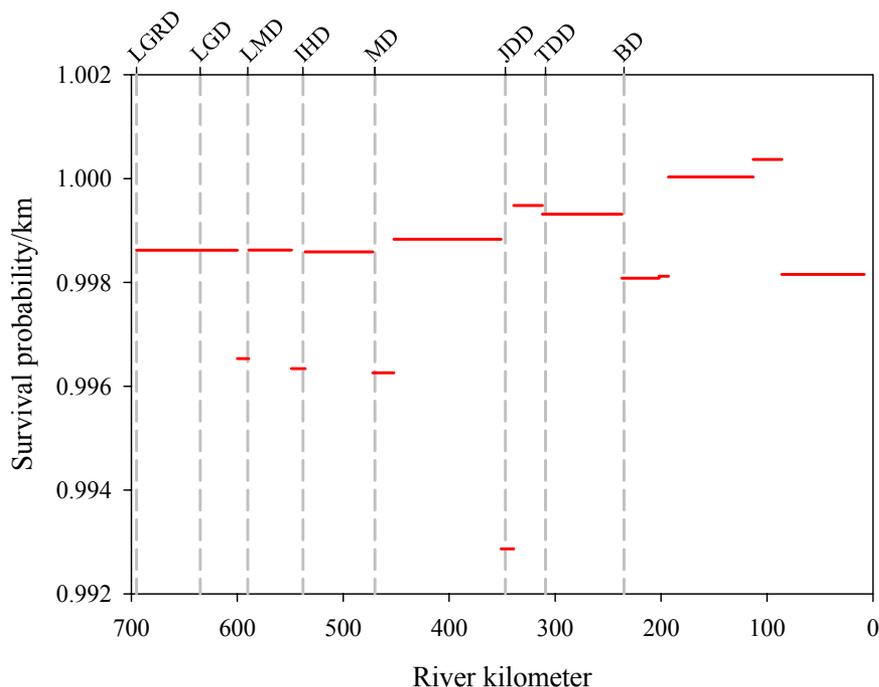


Figure 8. Survival probability per kilometer estimates for JSATS-tagged yearling Chinook salmon released into the Lower Granite Dam tailrace in 2008. LGRD = Lower Granite Dam, LGD = Little Goose Dam, LMD = Lower Monumental Dam, IHD = Ice Harbor Dam, MD = McNary Dam, JDD = John Day Dam, TDD = The Dalles Dam, BD = Bonneville Dam.



acoustic arrays at nearly any location in the river or estuary allows for estimation of system-wide survival (i.e., from release to the ocean) as well as survival over smaller spatial scales (e.g., reservoir and project survival). Acoustic arrays at hydroelectric dams also allow for collection of detailed fine-scale behavior in the forebay near the dam and accurate determination of route of passage (and subsequent associated route-specific survival estimation), while the PIT tag system detects only guided fish that pass through JBF systems or other relatively confined areas (e.g., the corner collector, a 4.6-m-wide concrete fish bypass channel, at Bonneville Dam).

Although several other acoustic telemetry systems currently exist, the JSATS is unique in several ways. A major difference between the JSATS and other existing bio-telemetry products is that all components (including transmitters, autonomous and cabled receiver systems, and replacement batteries for receiver systems) are non-proprietary and are specified in enough detail to allow for competitive procurement. As Grothues (2009) pointed out in his review of acoustic telemetry technology, proprietary interests have hindered optimization

Table 5. Comparison of microacoustic transmitters currently available (January 2009) on the market.

System	Model	Frequency (kHz)	PRI (s)	Weight in air (g)	Weight in water (g)	Dimensions (mm)	Tag life (d)	Detection range (m)	Power (dB)
JSATS	SS130 ^a	416.7	3	0.43	0.29	5.2 x 12.0 x 3.7	22	300 ^b	156
			5				30		
			10				55		
			30				55		
HTI	795s	307	3	0.65	0.34	6.7 x 16.4 x 6.7	15	up to 1000 ^c	142
			16				28		
HTI	795m	307	3	0.75	0.4	6.8 x 16.5 x 6.8	15	up to 1000 ^c	142
			16				28		
HTI	795E	307	3	1.5	0.8	6.8 x 21.0 x 6.8	25	up to 1000 ^c	148-150
			16				35		
Lotek	MAP6_1	200	1.3	0.9	0.6	6.2 x 13.0 x 6.2	7	NA	NA
			5.1				24		
			15.4				51		
Lotek	MAP6_2	200	1.3	1.1	0.7	6.2 x 15.0 x 6.2	4	NA	NA
			5.1				14		
			15.4				34		
Vemco	V7-1L	69	30	1.4	0.7	7 x 18 x 7	24	292 ^d	136
Vemco	V7-2L	69	30	1.6	0.75	7 x 20 x 7	52	292 ^d	136
Vemco	V7-4L	69	30	1.8	1.0	7 x 22.5 x 7	77	292 ^d	136 ^d
Vemco	V9-6L	69	60	2.9	1.6	9 x 21 x 9	79	418 ^d	142
Vemco	V9-6L ^e	69	60	3.1	2.0	9 x 20 x 9	120	418 ^d	142
Sonotronics	PT-1	69-83	1.0	1.25	0.6	7.1 x 16 x 7.1	7	300 ^f	129-133
Sonotronics	PT-2	69-83	1.0	1.7	1.0	7.1 x 19 x 7.1	12	500 ^f	132-136
Sonotronics	PT-3	69-83	1.0	2.0	1.0	7.8 x 19 x 7.8	21	750 ^f	132-136

a Vendor: Advanced Telemetry Systems

b Distance at which 20% of expected detections were received in freshwater. Transmitters have been detected at distances of 800 m.

c As reported on HTI web site.

d As provided by the range calculator on the Vemco website.

e From Rechisky et al. 2009

f from vendor website

NA - Not available from the manufacturer.



JSATS acoustic transmitters, with hand for scale.

of acoustic telemetry equipment development and use in certain areas. Through research and development, the USACE has established technical specifications of receivers and acoustic tags (e.g., size), which have been released to the biotelemetry market through an open-competitive procurement solicitation. Vendors who can produce components at a reasonable price are selected to produce prototypes, which are then subjected to rigorous acceptance testing. Upon successful completion of this step, the vendor who produces the highest-quality product at an acceptable cost is awarded a contract for production of the specific component. This strategy has led to reductions in transmitter cost and size. Transmitter cost decreased by about 28% between 2005 and 2008, while tag size decreased about 30%. The average cost of transmitters in 2008 was US\$215 per tag, down from \$247 in 2007, and a reduction from \$300 in 2005. The cost of JSATS tags in 2008 was less than that of other available microacoustic transmitters by \$40 to \$135 per tag. The competitive procurement actions for 2008–2009 transmitters resulted in the production of transmitters that weigh 0.433 g in air and are the smallest tag of its kind on the market (Table 5). These transmitters not only are smaller and more cost-effective, they also compare well with other available tags in terms of detection range and tag life (Table 5). It should be noted that the data presented in Table 5 are based on our direct measurements of JSATS transmitters and primarily on information from vendor Internet sites or published literature for other transmitters. One manufacturer (Lotek) was not willing to provide us with the power output information for its transmitters, so it is not included in Table 5. Finally, detection range data in Table 5 are based on field data collected with the JSATS and vendor-reported information for other transmitters, and may be best-case in some instances. Detection range in acoustic telemetry is influenced by environmental conditions and varies considerably (Shroyer and Logsdon 2009); therefore, the range data in Table 5 should be viewed with caution.

Another commonly used acoustic telemetry system is manufactured by Vemco. This system has recently been used by the

Pacific Ocean Shelf Tracking (POST) project (e.g., Rechisky et al. 2009) to estimate early ocean migration timing and survival for Chinook salmon smolts emigrating from the Columbia River. The Vemco system differs from the JSATS in several fundamental ways, each system having strengths and weaknesses. The JSATS was designed, developed, and optimized to address resource management questions related to the migration behavior and survival of small fish migrating through relatively fast and often shallow freshwater and into saltwater. It works well in these environments. The Vemco system used in the POST studies is better suited for use in the ocean environment and appears to work well for smaller numbers of larger fish in deeper and slower waters, such as those on the Pacific Ocean shelf.

A fundamental difference is the frequency in which these systems operate (Vemco at 69 kHz, JSATS at 416.7 kHz). A benefit of the lower frequency Vemco system is a greater detection range than the higher frequency JSATS, especially in deep marine waters. However, lower frequency transmitters require a larger acoustic element (transducer) and more power to generate the acoustic signal; resulting in a larger and heavier transmitter than the higher frequency transmitters. The net result is that the transmitters used in POST studies of juvenile salmon behavior and survival (e.g., Rechisky et al. 2009) are over seven times heavier (3.1 g in air) than JSATS transmitters (0.43 g in air). Survival estimation models used in most studies conducted with marking animals have a host of assumptions that must be met for the estimates to be valid. For example, the tag must not influence the chance for “recapture” and the animal tagged must be representative of the population of interest (Cormack 1964; Jolly 1965; Seber 1965). Use of larger tags is more likely to result in violations of these assumptions than use of smaller tags, particularly when the species or life stage is relatively small, such as juvenile salmonid smolts.

Other relevant differences between the transmitters used in the POST and JSATS are pulse rate, tag life, and signal encoding approach. The tags used in the POST project by Rechisky et

al. (2009) were intended to have sufficient tag life for the tagged fish to transit from the Columbia River to the Pacific Ocean off Alaska (120 days). In contrast, JSATS transmitters are typically programmed to transmit long enough for the fish to emigrate from the Columbia River basin into the near shore Pacific Ocean (e.g., 30 days). Tag life is a function of (among other things) the size of the tag (primarily batteries) and pulse rate of the tag. The tags used by Rechisky et al. (2009) transmitted at a nominal pulse rate of 60 seconds (individual pulses vary in timing at $\pm 50\%$ of the nominal pulse rate), while the JSATS transmitters used in this article transmitted at a rate of once every 5 seconds. In areas where fish may be moving quickly, such as in free-flowing portions of the Columbia River downstream of hydroelectric dams, detection probability is higher for tags transmitting at a higher rate. Finally, the encoding scheme of tags used in POST and JSATS studies is different. The tags used in the POST system emit a pulse-interval-coding (PIC) signal in which the time between pulses is used to identify a unique tag code. The PIC encoding approach enables the vendor (Vemco) to produce economical receivers but limits the number of transmitters that can be detected by a receiver when multiple tagged animals are near a receiver for a short period of time, due to collision of tag signals (Grothues 2009). For example, the Vemco website (Vemco 2009) shows that due to transmitter signal collisions, the time required to detect 15 tags with a nominal delay between transmissions of 60 seconds (like those used by Rechisky et al. 2009) would be 24 minutes. This may not be a problem in areas where few fish are tagged and/or residence time around receivers is high. However, in Columbia River basin studies there are often over 20,000 JSATS-tagged juvenile salmonids released over the course of a few months each year. These studies require high detection probabilities in river areas with water velocities in excess of 3 m/s. A JSATS transmitter with a PRI of 5 s and a decode range of 300 m would transmit 40 signals if it passed through the center of a receiver's "listening" zone at 3 m/s. A Vemco transmitter with a mean PRI of 60 seconds and an assumed decode range of 600 m would transmit approximately six signals (though individual "pings" could be anywhere from 30 to 90 seconds apart) while passing its detection zone at 3 m/s. The BPSK encoding used in JSATS, a form of phase modulation, is more robust than PIC encoding to background noise and is much less susceptible to tag collision problems due to the short duration of each transmission of the complete tag code. A single complete tag code in a JSATS tag is transmitted in 744 μ s, while it takes roughly 3 to 5 seconds to complete a single PIC tag transmission of the 69 kHz Vemco transmitter.

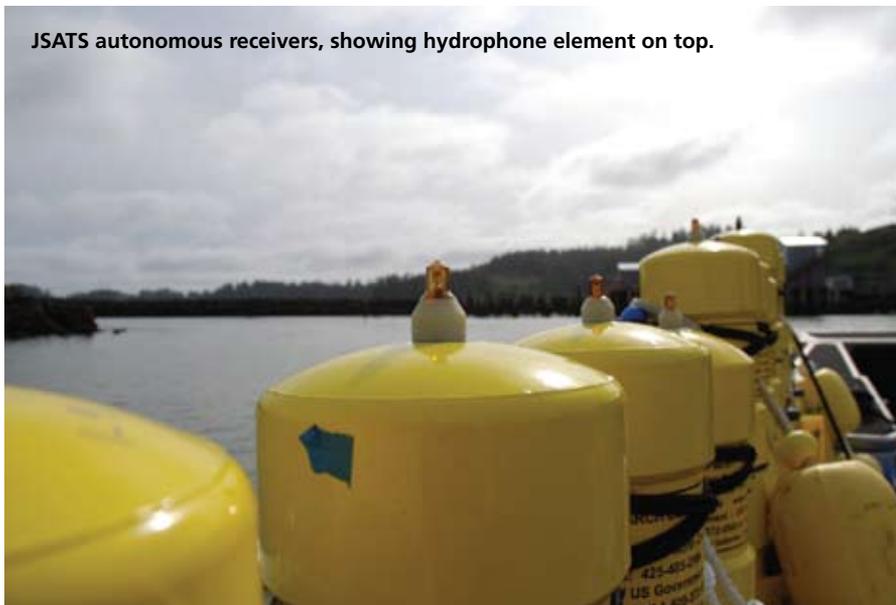
The reduction in size of the JSATS transmitter to 0.433 g represents a substantial advancement in acoustic telemetry equipment. Results from a laboratory study conducted to determine the transmitter burden (transmitter weight/fish weight) that is suitable for juvenile salmonids (Brown et al. in press) indicated that survival of implanted individuals may not be affected if transmitter burdens are maintained at or below 7.6%. If this criterion were followed, it would allow juve-

nile salmonids as small as 6.5 g to be implanted with the 0.433-g JSATS transmitter, whereas the next smallest available acoustic transmitter (0.65 g) could be implanted only in fish weighing 9.7g or more. For example, in 2007, the majority (about 95%) of subyearling Chinook salmon sampled by the Smolt Monitoring Program (www.fpc.org/) at Lower Granite Dam were large enough for implantation with the current 0.433-g JSATS transmitter, whereas only about 81% were large enough for implantation with an acoustic transmitter that weighs 0.65 g. Using the same transmitter burden criteria, the transmitters used by Rechisky et al. (2009; 3.1g in air) would limit tagging to fish 46.3 g and larger. Telemetry studies using smaller transmitters are better able to meet a critical assumption that marked individuals are representative of the population of interest.

Traditionally, the use of acoustic telemetry has been limited by the high cost and large size of transmitters. However, the approach used by the USACE to competitively procure transmitters has resulted in large reductions of both the cost and size of JSATS transmitters. Another aspect of acoustic transmitters that has traditionally limited their use in studies of Pacific salmon has been the short functional life of tags. One of the greatest advantages to using PIT tags is the long life of tags, which are designed to last the life of the implanted animal. This feature allows researchers to estimate smolt-to-adult return rates of salmon PIT-tagged as juveniles as they return to freshwater and are detected in fish ladders equipped with PIT tag detectors (Burke and Jepson 2006).

Although the JSATS has been used successfully for several years, further development of system components is ongoing. The biological effects of the tagging on the host fish, the effect of the fish on the tag, and consideration for the effects of different environments on detection capability and receiver durability continue to be the primary areas of emphasis in development. Extensive field and laboratory studies are currently underway to understand any deleterious effects the current tag has on the host fish and how these effects can be addressed in experimental design to eliminate or minimize bias in study results. These studies are providing information on the long-term effects of tag presence on growth, tag retention, tissue response, and survival.

JSATS autonomous receivers, showing hydrophone element on top.



Several other important development efforts are also ongoing. A receiver package that can be deployed in the Columbia River plume and near-shore ocean to detect JSATS-tagged fish after they have exited the mouth of the Columbia River has been developed and successfully tested in the Pacific Ocean. A near-shore ocean array would extend the temporal and spatial scale for evaluating the delayed or latent mortality associated with various passage histories of fish migrating through the FCRPS. The feasibility of detecting JSATS codes with components (e.g., hydrophones and cables) from other types of receiving equipment (e.g., non-JSATS equipment already owned by the USACE) also is being examined. In addition, because the USACE is beginning to use this tool to answer a host of resource management questions, additional efforts are ongoing to standardize surgical tagging and handling techniques, receiver deployment protocols, tagging and detection data input, and data filtering, analysis protocols, and statistical models.

CONCLUSIONS

The Juvenile Salmon Acoustic Telemetry System was developed to address critical uncertainties on the effects of the FCRPS on migrating fishes. Prior to its development, there was no existing technology with which to conduct movement and survival studies of small fish migrating long distances (~600 km) from freshwater to saltwater. Although the JSATS already has contributed new information to the regional fishery managers and operators of the hydroelectric system, development activities continue to enhance the utility of this new system. From 2006 through 2008, approximately 60,000 JSATS-tagged juvenile salmonids were released into the Snake and Columbia rivers to further the region's understanding of how juvenile salmonids move through the Snake and Columbia rivers and how the behavior and survival of these fish is influenced by the configuration and operation of this large hydroelectric system.



JSATS receivers and related mooring equipment loaded on a research vessel in the Columbia River estuary.

Although the JSATS was developed to address information needs related to juvenile salmon in the Columbia River, it could also be used to conduct biotelemetry studies on aquatic organisms in many environments in which it is desirable to have very small active transmitters and autonomous or cabled receiving systems. Because the basic function of the system is nonproprietary, users can define criteria that meet specific needs (e.g., longer life tags, different receiver shape or weight) to their vendor of choice. Ongoing JSATS development and procurement activities will ensure that this new system continues to evolve to satisfy the demand for better technology to address biotelemetry questions in many aquatic environments well into the future.

Reference to trade names does not imply endorsement by the authors or their organizations.

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